RELIABLE TUBE DEVELOPMENT

TIMOTHY J. KEEN

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RELIABLE TUBE DEVELOPMENT

by

Timothy Joseph Keen

Lieutenant, United States Navy

Submitted in partial fulfillment
of the requirements
for the degree of
MASTER OF SCIENCE
IN
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PREFACE

In these times the world is coming to depend heavily on the science of electronics. In communications, manufacturing, military forces, and many other fields, electronic equipment is taking, or has already taken, vital roles. Our well being and our economy are dependent upon our advancement of the technology of this science. Equipment is becoming very complex, and in some cases has been given a degree of intelligence. However, as long and as strong as this chain has grown, it has a weak link. The weak link is the electron tube, the basic component of all electronic equipment. There is urgent need of strengthening this link by making electron tubes more reliable.

The semi-conductors and magnetic devices show promise of answering this need. Their simplicity and extremely long life make them likely candidates for filling many of the roles presently played by electron tubes. However, at the present state of the art, electron tubes must carry the burden, and to do so their reliability must be improved. It is the purpose of this paper to show the causes of poor tube reliability, what can be done about it, and what has been done about it.

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CHAPTER I

INTRODUCTION

Complicated electronic equipments, using many hundreds of tubes and perhaps thousands of other components, can often be completely inactivated by a single component failure. Compared to the failure rate of electron tubes, the failure rates of other components are insignificant. Tubes, as we know them today, are inherently fragile, and their useful life is short compared to other components. The problem to be treated here is twofold. We wish to make electron tubes both rugged and long-lived in order that they may be termed "reliable". Ruggedness and long life are related, but they are not necessarily interdependent. The reasons for this will be developed later.

An investigation of tube employment environments will disclose two major divisions, stationary and mobile. Stationary includes any environment which never moves relative to the earth. The mobile environment includes anything that does move, on land, at sea, or in the air. The reliability problem in stationary equipment is primarily that of gaining long life expectancy. The tubes do not have to be rugged because there are no high amplitude acceleration forces or other radical conditions to have destructive effects on them. In the mobile environment the physical forces are factors which must be considered. They are: wide temperature

ranges, vibration, and shock. These forces require our "reliable" tubes to be rugged as well as long lasting.

In the stationary case, tubes can be made more "comfortable" as they do their tasks. The equipment can be spacious to provide plenty of cooling (or cooling can be conveniently introduced by blowers, refrigeration, etc.). The units are virtually free of vibration and shock, and in general the electrode and heater voltages are quite stable. Under these conditions, old age is the only major problem. Deterioration is gradual and can be predicted to a certain extent. Even so, the electron tubes are still the most troublesome components in the equipments.

Electron tubes in vehicles have a hard, rough life compared to the stationary tubes. In the moving equipments there are many causes for "sudden death" or "catastrophic" failures. Equipments are built with emphasis on small size, lightness of weight, and low power requirement. These factors lead to inadequate cooling, short vibration periods, and unstable or improper voltages. The actual vehicle may compound the temperature problem by causing the equipment to be installed in a space with too high an ambient temperature. All moving vehicles have vibrations of varying amplitudes and frequencies. Ships are found to have vibrations ranging from zero to 100 cycles, and aircraft have vibrations up to 10,000 cycles. Motor vehicles have frequencies of vibration in the range from zero to 1,000 cycles. These values were deter-

mined by research projects conducted by the Bureau of Standards. These vibrations can contribute both to tube failure and to unsatisfactory tube performance. Failures are usually due to mechanical breakdown, such as fatigue failure, and poor performance may manifest itself in the form of excess noise.

High acceleration shocks are also present in mobile environments, whereas they are virtually non-existent in stationary set-ups. All vehicles suffer jolts and bumps, and military vehicles experience extremely severe shocks due to gunfire, explosions, etc. Under these adverse conditions the tubes must continue to function. Portable equipment, whether used in vehicles or not, must be expected to experience abnormally strong shocks also. The Bureau of Standards conducted some simple experiments to investigate the effects of handling and transport on electronic equipment, and they found that dropping a unit of equipment to hard earth from a height of four feet introduces accelerations up to 600g. The same fall to concrete brings the shock up to 1,000g for an instant. This organization found 70% failures in tubes subjected to 700g shock. This certainly demonstrates the need for rugged tubes when one considers the usual handling that any portable equipment receives, particularly in military transport and use.

The high price placed on lightness of weight and low power requirements in mobile equipment tends to cause designers

to use tubes in applications designed for peak performance of the tubes. That is, a new tube, in good condition, will perform as required, but as the tube ages and deteriorates slightly, the symptoms of old age cause the tube to be a failure before it would fail in a less demanding circuit. The tube could be taken out and put in service elsewhere under less rigid requirements. This is poor design, however it happens frequently. Better tube life - slowing the rate of deterioration - would help in this case, though it is not the complete solution. Circuits should be designed with tolerance to allow for some decay of performance. Occasionally, equipments require tubes to operate at <u>greater</u> than rated values. Only a design change in this case can eliminate certain circuit failure.

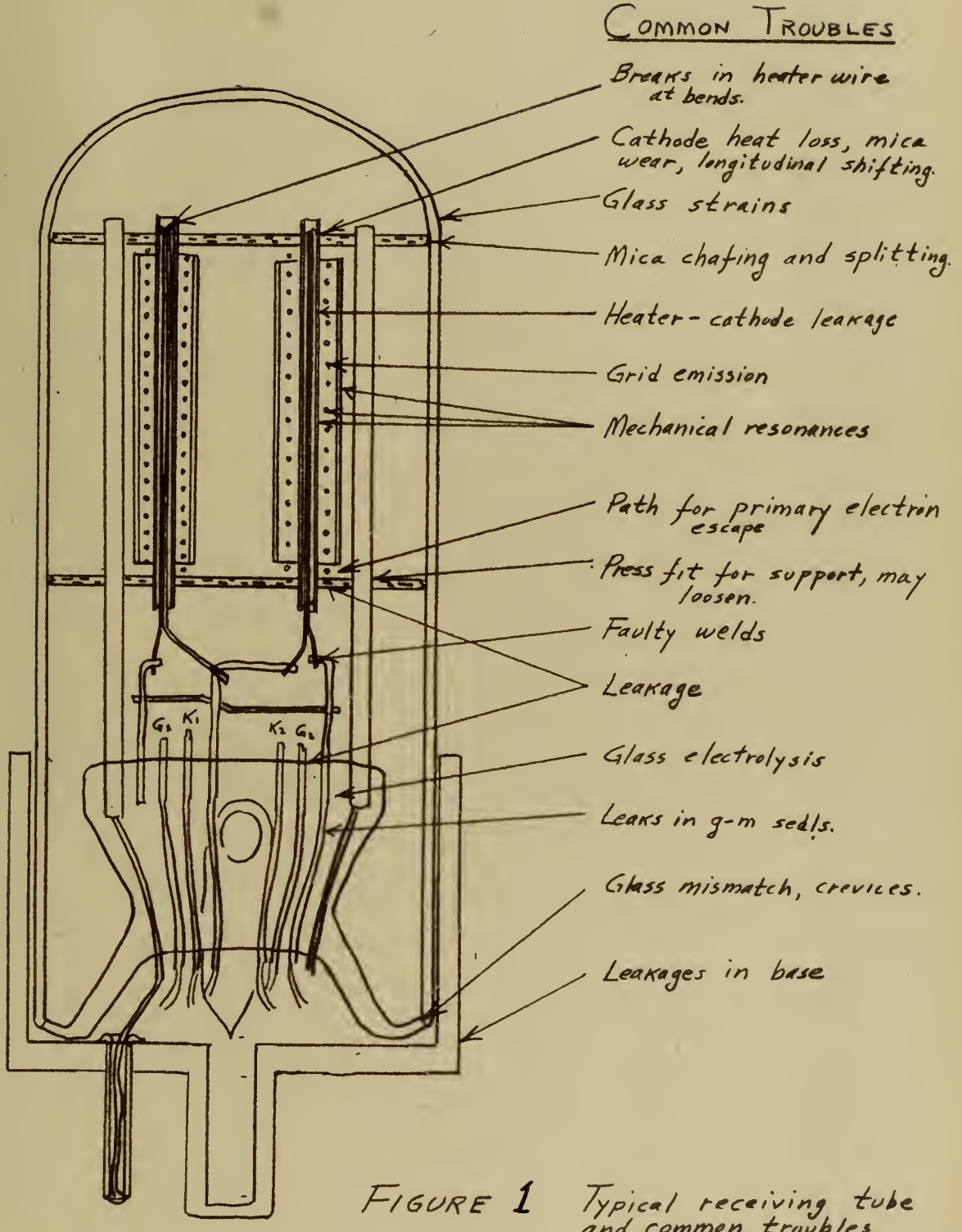

FIGURE 1 Typical receiving tube and common troubles.

CHAPTER II

TUBE RUGGEDNESS PROBLEMS

The most obvious problem in ruggedness is the envelope itself. Most tubes have glass envelopes and are therefore fragile. Even metal tubes use glass seals which prove to be an Achilles Heel. However, the basic mechanical properties of glass, per se, do not usually lead to glass failure. It is usually the steps in the envelope construction which promote failure. When glass breaks occur, they most often occur at points of excess stress or strain caused by manufacturing techniques. Glass bulbs with cylindrical walls and near-hemispherical ends have "strain rings" at the junctions of straight portions and rounded portions. There are also regions of expansion mismatch where bulbs are sealed to the glass bases (containing glass-to-metal seals) because they are usually different glasses. Tip-off seals invariably have deep and narrow crevices which are under strain, and another residual strain, termed "thermal", is caused by differential contraction of glass near welds in relation to glass farther away. A study by Rowe [15] has shown that most tube glass failures can be attributed to these four conditions. A strained area may fracture easily when scratched or struck. Careful processing techniques are necessary to minimize these stresses and strains.

Rowe also found a significant number of envelope failures

to be due to poor glass-to-metal seals. Seals will be discussed later in this paper.

After a tube has been assembled, most of the stresses and strains can be relieved by annealing processes, but it is not possible to maintain this relieved condition in all the different temperature situations to which a tube will be subjected in service. In the manufacturing stage some strain must be allowed to remain; that is, the bulb must be in compression about the base in the button stem types.

The second most obvious failures are heater or filament open circuits. These breaks are fatigue fractures at inherent weak points such as sharp bends and spot weld connections. The breaks occur as a result of vibration, physical shock, or thermal shock. Thermal shock is an important consideration in applications where frequent of-off cycling occurs. When heater voltage is abruptly applied to a tube, the entire heater assembly experiences thermal shocks and strains caused by expansion and uneven heating of the heater wire. The expansion also causes physical abrasion of the heater insulation against the cathode sleeve.

Other catastrophic or sudden death failures are more subtle in that a simple examination fails to reveal their causes. These are internal short or open circuits resulting from broken welds, loose electrode members, grains of carbon or cathode coating which suddenly lodge in a position to short circuit electrodes, or insulation breakdowns. Spot welds,

though emminently practical from a production standpoint, have a small but significant probability of failure from faulty welds. A good spot weld is very strong, but a poor spot weld will look just as good if it holds at all, so it will pass a superficial inspection. The probability of tube failure due to faulty welds is the weld failure probability multiplied by the number of welds in the tube, and tubes may average about twenty spot welds.

Loose electrode members can result from wear of mica punching dies, wear of mica in service, or simply lack of precision in manufacture. Most receiving tubes rely on press fits to hold grid support rods and cathode sleeves in correct position. Shocks or prolonged vibration may wear the mica and aggravate a loose fit condition.

Short circuits due to grains of conducting material are naturally most common in close-spaced tubes, such as radio frequency pentodes. Carbon particles may come from electrodes which have been deliberately carbonized for heat dissipation purposes, or they can come from lint which adhered to some tube element during assembly. Air-borne lint can lodge in a tube assembly and be carbonized in the bake-out or out-gassing processes. Air filtration and cleanliness precautions in assembly rooms will solve this problem.

The most common insulation breakdown point is heater-to-cathode. The heater insulation coatings are hard but brittle, and the conditions under which they must exist are certainly

trying. Heaters usually operate well above 1,000°C, and the coatings are subject to flexures of the heater wire as well as severe thermal shock. It is not surprising that heater insulation is a weak point in tubes. In a missile guidance project, BENDIX AVIATION CORP. established a special tube testing program to select highly reliable tubes from stock [3] Over half of their tube rejections were based on faulty heater-cathode insulation.

Another phase of tube trouble related to mechanical short-comings is the presence of microphonic electrical outputs. Microphonics are caused by any mechanically produced disturbance of the electric fields between cathode and anode. Ordinarily one thinks of distinct mechanical resonances which cause field fluctuations and can be traced to some particular electrode. This is only a part of the problem. Research studies by the PHILCO CORPORATION [8] have shown that just as much microphonism is caused by presently undetermined factors as is caused by definitely known mechanical resonances. This was clearly indicated in their experiments wherein series of identical tubes exhibited very slight correlation in their microphonic properties. The PHILCO method of investigation was as follows. An operating tube was subject to variable frequency vibration, applied to give the tube circular motion in a plane perpendicular to its longitudinal axis. The tube output was coupled to the vertical deflection plates of an oscilloscope while the horizontal plates were

arranged to provide deflection proportional to the vibration frequency. This gave a line spectrum indication of microphonic output. The traces were photographed for comparison (frequency markers were introduced along the trace). The results did show a few common high points which indicate outputs due to "gross" factors, such as grid resonance, but all the photographs showed many smaller output peaks which appeared to have no coherence from tube to tube. The PHILCO researchers are presently striving to analyze these "subtle" factors.

CHAPTER III

LONG LIFE PROBLEMS

There are two primary contributors to the decay of tube performance. One is the falling off of transconductance, and the other is the appearance of leakages. The decay in transconductance is most important, and it is largely caused by the build-up of residual gases within the tubes. The gas molecules are bombarded and ionized in the electron stream, and positive ions strike the cathode, "poisoning" it.

Another effect of the ionized particles is inverse grid current. The arrival of a positively charged ion causes an electron flow into the grid, and this momentarily decreases grid bias on the tube which raises cathode current. Large values of grid resistance are common, and only one microampere through one megohm decreases bias by one volt. If a tube becomes too gassy, and if the cathode has no protective resistor, the ion flow may cause it to "run away" because of inverse grid current. Further, if the ion energies are high when they strike the grid, the situation may be worsened by electron emission from the grid.

Cathode poisoning is usually oxidation of the free barium in the cathode. Ordinarily a properly operating cathode maintains a small surplus of free barium ions (estimated to be 0.2% of the barium ions present). These free ions are continually lost at a slow rate by evaporation, but the cathode

has the property of expelling a like number of oxygen ions, which are recombined with the lost barium ions somewhere else in the tube, or they go to a getter. Thus the small supply of free barium is maintained. However, if other oxygen ions are liberated within the tube, they tend to go to the cathode and combine with these free barium ions, and emission falls off. The cathode is then said to have been poisoned. Poisoning results in low emission which causes decay of transconductance.

Another cause of decrease in transconductance is the formation of "cathode interface" [3,12]. This interface is the junction surface between core metal and coating in an oxide-coated-cathode. There is always some tendency for interaction between two different materials which are joined under high temperature conditions, and in this case, where the two materials are usually nickel and barium-strontium carbonates, the interaction results in the formation of an interface layer of barium silicate. The silicon comes from the silicon impurities in the nickel. Pure barium silicate is a good insulator, and the presence of this material is indicated by an increase in internal resistance of the cathode. A shunt capacitance effect is also present. As interface progresses, the apparent resistance increases while the apparent capacitance decreases. The cathode interface phenomenon is only important in tubes which are operated at very low or zero current a substantial part of the time, such as tubes used

in pulse applications or digital computers. This is explained by the currently accepted theory that a current conducting cathode has a flow of positive barium ions to the interface layer. These ions act as an impurity agent to prevent the barium silicate from becoming a good insulator. In a tube operated with no standing current, the barium silicate layer builds up with no impurities, and the transconductance of the tube is adversely affected. Work has been done to eliminate this effect, exploring two possibilities. One course is to eliminate the silicon content, and the other course is the introduction of activating agents which produce high conductivity interface. American authors claim that silicon-free nickel solves the problem, and indeed tube manufacturers are acting on this premise, but British authors find that this is not completely efficacious. Silicon-free cathodes are difficult to activate under manufacturing conditions. For further information on cathode interface, the reader is referred to the various papers published on the subject[1].

The residual gases which shorten tube life are present because of several gas sources within tubes. All the materials used in tube construction can contain free molecules of

1. Waymouth; JOUR OF APPL PHYS, Vol.22, 1951, 22.
   Eisenstein; JOUR OF APPL PHYS, Vol.22, 1951, 138.
   Raudorf; WIRELESS ENGINEER, Vol. 26, 1949, 331.
   Eisenstein; WIRELESS ENGINEER, Vol. 27, 1950, 100.
   Eaglesfield; ELECTRICAL COMMUNICATIONS, Vol.28, 1951, 95.
   Metson, Wagener, Holmes and Child; JOUR of INST of ELECT ENGRS, Vol.99, Pt.III, 1952, 69.
   Child; P.O. ELECT ENGRS JOUR, Vol.44, 1952, 176.

gas. Some gases are condensed on surfaces (adsorbed), some are in chemical combination with the material (absorbed), and in metals and insulators there are usually cracks and crevices which contain gas (occluded). In the process of "outgassing" a tube, the tube is heated to cause these gases to be liberated and pumped out. The usual receiving tube outgassing is done by R.F. eddy current heating of the metal parts, and brief flame heating of the glass envelopes. In better tubes, the entire tube is baked for a period of time at several hundred degrees centigrade. Bake-out time ranges from as low as fifteen minutes for receiving tubes to hours or days for large tubes. Glasses should be heated to about 90% of their annealing temperature to drive off adsorbed gas. Metals may be degassed by heating to about 50% of melting temperature [17]. The principle gas component is carbon monoxide (30 to 90%). The remainder is largely nitrogen, which comes off at higher temperatures than carbon monoxide. The more thoroughly the out-gassing is done, the less residual gas a tube has to shorten its life.

Most tubes contain "getters" to absorb residual gases. Getters are metals which have great affinity for gas. Barium is used extensively as a "flash getter". The getter material is usually held in some sort of a cup or cradle during assembly and pumping, then the cup is heated to about 700°C to vaporize the metal and cause it to deposit in a thin film on the tube envelope or some other surface within the tube - a

surface whose leakage resistance is unimportant. This is the shiny area seen on the walls of many receiving tubes. In large scale manufacturing of low cost tubes, the getter is relied upon to "clean up" tubes after relatively poor vacuum pumping. This sometimes leaves the getter with little ability to keep up its cleaning action, so the residual gases can accumulate. The getters are also limited in the kinds of gases they will absorb. No single getter material will absorb all gases, and the noble gases cannot be absorbed by any getter.

There are many materials other than barium which have getter properties. Some of them are: strontium, caesium, magnesium, tantalum, columbium, zirconium, titanium and thorium. The flash getters are usually used in receiving tube types, and they are metals which vaporize at reasonable temperatures. Other basic getter types are the "bulk" getter and the "coating" getter. The bulk getter is a heated sheet or wire, usually of columbium, zirconium, or titanium. Coating getters are metal powders sintered onto electrodes which operate at the proper temperatures. Many high power tubes have getter coatings on the anodes. All the bulk and coating getters have their own peculiar operating temperatures. Some will liberate absorbed gas if operated too high or too low. They can also be selective in absorbing only certain gases at certain temperatures. For instance, zirconium is an excellent hydrogen getter at 400°C, but at 1400°C it absorbs carbon monoxide,

carbon dioxide, oxygen, and nitrogen. So zirconium is best utilized when it has a temperature gradient covering the entire range from 400°C to 1400°C. These specially heated getters, though excellent in performance, are not practical in ordinary receiving tubes.

Another basic division among getters is the manner in which they absorb gas. Some actually corrode, such as barium, while others dissolve the gas within their bulk. Zirconium is a "solution" getter. For an excellent summary of getter materials and their properties, see reference [5].

It is inescapable that "hard" pumping is a necessity for long life expectancy, even though active getters may be present. Getters do help, but they must be allowed a reasonably clean tube to start with. High operating temperatures cause residual gas build-up by continuing the bake-out process. Baking out liberates captive gases at a decaying rate, so it can be seen that no amount of baking will completely clean the envelope and electrodes. When envelope or electrode temperatures exceed design values, the gases are evolved from the glass or metal. If the high temperatures continue long enough, the getters will fail to cope with the gases, and ionization will take place, poisoning the cathode.

Tube shields, improperly used, can contribute to excessive envelope temperatures, hence gas build-up. If shields are poorly connected to the chassis they can act much like "storm sashes". Koch reports [12] that tube shields with

poor thermal connections can raise bulb temperatures as much as 50°C. In general, tube envelopes should be kept below 175°C if long life is to be achieved.

It should be mentioned that a great deal of gas is released by oxide cathodes during the initial phases of cathode activation. The oxides are really applied in the form of carbonates because the oxide states are hygroscopic and will combine with any moisture present to form hydroxides. This would hinder activation of the cathodes after evacuation. When a tube has been pumped to some extent, the cathode is "activated" by the process of heating it. This heating is done in a timed sequence of increasing heater power steps. In high quality tubes this is precisely and carefully done. The cathodes are heated well above normal operating temperature, and the carbonates are broken down to carbon monoxide, carbon dioxide, and the desired barium and strontium oxides. The carbon monoxide and carbon dioxide are quickly pumped away. Activation is actually a matter of causing the oxide coating to reach a state of chemical equlibrium which provides the desired excess of free barium ions. Considerable research is being done to investigate this process so that it may be better understood and therefore better controlled. Present day methods of activation are more or less the results of trial and error which yielded rules of thumb by which activation is programmed. There is an infinite number of time-temperature schedules which may be attempted, and very possibly our pres-

ent methods are inferior. More knowledge of cathode chemistry is almost certain to result in improvement.

The gases from cathode coatings are not a source of residual gas in the long life problem.

Another troublesome source of gas is mica. Most receiving tubes use mica wafers as spacers and as supporting elements for the electrodes. Mica is an excellent material for these purposes because of its insulation qualities and resistance to heat deterioration. Its thermal conductivity is also good, but this is a disadvantage when the mica also supports a cathode sleeve, and it frequently does. The mica in contact with the cathode causes a loss in heating efficiency, and the heat flow causes uneven cathode heating by lowering the temperature at the ends of the cathode sleeve, or wherever the mica happens to contact the cathode. Uneven cathode heating effects are obviously unfavorable to best performance because the transconductance varies along the cathode length, and the low temperature points are especially vulnerable to cathode poisoning and ion bombardment damage. This is because the electron cloud surrounding a low temperature area is not dense enough to neutralize many of the positive ions.

Mica consists of many layers of silicate material which in itself is not a source of trouble, but moisture is usually present between these layers, and "bake out" cannot eliminate it. The moisture is released when vibration or shock cause the edges of the mica to become burred or split where it is

in mechanical contact with some other tube part. Hence, vibration and shock can cause residual gas accumulation to shorten tube life in those tubes which use mica. In laboratory tests, tubes go "soft" very quickly under sustained vibration which causes micas to strike the envelope. This writer had experience in making such tests on type 6SN7 tubes produced by a number of different manufacturers. Mounting four operating tubes of different makes in a single jig, and vibrating them all together, definitely showed the tubes with direct mica-to-glass contact to go soft quickly. The mica could be observed to be burred and split where it had touched the envelope. The tubes which incorporated features to minimize or prevent mica-to-glass contacts lasted much longer.

Heater-cathode leakage, though ordinarily a catastrophic type failure rather than a gradual deterioration problem, can contribute to the gradual build-up of residual gases.

One more cause of decreased transconductance with tube aging is the loss of "active" material from oxide cathode coatings. The actual emission of electrons is from free barium atoms present on the surface. These metals do vaporize eventually and cause a decrease of emission.

The vaporization of barium leads to shortened tube life in another way. The barium deposits on insulating surfaces within the tube, and also on the tube envelope. Deposits on the glass seals in the vicinity of pin lead-outs and on insulators cause a decrease in interelectrode resistances which

adversely affects tube performance. It is also possible that these deposits can result in increased interelectrode capacitances.

Leakage effects can also be caused by glass electrolysis in the region of the tube pin lead-outs [20]. High glass temperature, and the existance of a voltage potential between two points in contact with the glass, will cause glass electrolysis. This process begins with a grey fibrous pattern appearing in the vicinity of the low potential point. The grey pattern spreads and turns black, and the dielectric properties of the glass deteriorate. Finally the glass becomes porous and catastrophe occurs - it cracks and vacuum is lost. Fortunately, glass electrolysis is not an urgent problem because a tube must have survived quite a long time before the effects of electrolysis can ruin it. However, electrolysis can be hurried by high glass temperature. Temperature is a critical factor. A change of 10°C can mean the difference between long and short life.

Glass-to-metal seals are significant trouble sources in the long life problem. They are common causes of gas leakage into the envelope. In receiving types these seals actually consist of fusion of glass with a coating of oxide on the metal part, except when the metal is tungsten, kovar (an alloy of nickel, cobalt, and iron, developed especially for sealing to glass), or copper. Good seals do not usually fail unless abused mechanically, but slow-leaking seals can get by inspec-

tions unless special test methods are employed. Rowe [15] reports finding many gassy tubes resulting from leaky seals in his "trustworthy valves" work.

CHAPTER IV

DESIGN AND MANUFACTURING CONSIDERATIONS TO IMPROVE RELIABILITY

One of the first design features to be considered to improve reliability is the choice of materials used. All the materials in a tube should be of the best practical quality.

The tube envelope, be it metal, glass, or ceramic, must be carefully processed and inspected. The material must be chemically pure to the extent that it contains no chemicals harmful to tube operation. For example, a trace of cadmium in some part of a tube using an oxide-coated-cathode will contaminate the cathode very quickly. Cadmium will combine with free barium to form an alloy which will not readily emit electrons. This type of impurity cannot be eliminated by any amount of cleaning. The material must be manufactured in a chemically pure state to avoid this pitfall.

An incident at Eitel-McCullough, Inc., points up this cathode sensitivity to cadmium. A few years ago many expensive tubes were ruined because of cathode poisoning in manufacture. Spectrographic tests indicated the presence of a minute trace of cadmium in the cathode coating. Production was stopped for several days until it was finally discovered that equipment maintenance men had made a routine replacement of spring clips which were used in the cathode coating operation, and the new clips had cadmium plated springs. The proximity of the cadmium to the cathodes was sufficient to poison

them. There are numerous other elements which will cause similar trouble.

Glass envelopes are the most common in use today. Glass has the advantages of transparency, chemical inertness, high resistivity, hardness, and workability. On the other hand, glass has many important disadvantages. It is brittle rather than tough, and it requires refined techniques to keep it from cracking. Though strong in compression, it is weak in tension. It is subject to several kinds of residual stresses, and glass-to-metal seals are never a simple problem.

If the tube designer chooses glass for the envelope, there are many choices of glass available. Glasses can be classified as hard or soft according to their softening temperatures. The use of a hard glass will allow higher bake-out and operating temperatures, which provide advantages previously discussed. Also, the physical strength of glasses varies considerably. A difficult part of the choice of glass is the ease of working. The best possible glass for a tube envelope may be difficult to use, requiring complicated processes or exceptionally high skill on the part of glass workers. The glass-to-metal seals must be carefully designed. The expansion characteristics of the glass and metal involved in a seal, such as an electrode lead-out, must be matched within very small limits of difference if vacuum is to be maintained. It is desirable to have lead-outs as large as possible to reduce resistance, provide strength, and most im-

portant, to allow heat conduction from the electrodes. The larger the lead-out size, the more critical becomes the expansion characteristic matching problem.

It is sometimes possible to check the tightness of a seal by visual inspection. In the oxide seals the color is an indication of quality. Quality control tests may be better performed by placing tubes in high pressure (100 psi) hydrogen or helium atmospheres. This usually accelerates slow leakages and allows quick detection. Although it does not affect reliability, it is appropriate to mention the fact that large lead wires decrease lead inductance which is important at high frequencies.

Ceramic tube envelopes have excellent qualities. They are not now in general use except as relatively small parts of envelopes consisting primarily of metal. Ceramic sections are used as "cavity windows" in large klystrons, but no small receiving types in general use are made of ceramics. An extensive program, however, is currently being sponsored by the military services to develop all-ceramic tubes. Though expensive, ceramic tubes will have many advantages from the reliability aspect. Ceramic materials can withstand great heat and therefore do not limit the bake-out temperatures. Ceramic tubes can be baked out at 500°C for long periods, whereas glass envelopes are limited to somewhere around 200°C. Ceramics are not subject to electrolysis, have very high leakage resistance, and they are very strong. At the present state

of the art, the ceramic materials commercially available are of very poor quality for high vacuum applications. The difficulty lies in the quality control exercised by the producers because their consumers have not demanded the quality needed in vacuum tube work. Tube manufacturers presently using ceramics have a very high rejection rate on the raw shapes received by them. Processes have been developed for metallizing ceramic surfaces in order that pieces may be joined by conventional brazing techniques. Because of their hardness, ceramic materials must be ground by abrasives or cut by abrasive wheels in order to shape them, but this should not prove to be a drawback because the pieces can be originally formed and fired in any desired shape. The efforts now being made to develop ceramic vacuum tubes will no doubt result in rather widespread use of ceramics in the near future.

If a tube design employs mica, the mica can be of excellent quality in the raw form, according to the care with which it is selected. Holland [11] found that certain micas were superior for tube use because they produced the least gas under shock conditions. He showed Brazil Clear mica to be best while Black Madagascar mica is worst, and his paper lists a good number of other micas in the order of their superiority. This work was done at RAYTHEON under Navy Contract NObsr 39367, and the project proved that the designer can do much to eliminate the gas problems associated with mica by avoiding conditions which permit chipping and splitting to take place. The

edges can first be improved by keeping the punching dies sharp. Mica wears dies very quickly, and the dulled cutting parts cause the edges of the cut mica to be frayed. Frayed edges are easily split and further frayed. A clean-cut edge will resist splitting. Also, the holes can be protected by staples or grommets to avoid any direct chafing of the mica edges. Some manufacturers have adopted these grommet and staple methods in the manufacture of their reliable tubes. Most ordinary receiving tubes rely on press fits of grid rods in holes in mica wafers to support the grids firmly. Unfortunately, this often produces a sawing action when the rod is pressed into the undersized opening, particularly if the grid rod is notched along its entire length. The use of grommets on the mica openings solves this problem and it also supports the grid rod in a positive fashion to prevent longitudinal shift under conditions of shock. In a multigrid tube such a shift could misalign the grids and radically change the tube characteristics.

If the mica wafers must be utilized as lateral support members against the tube envelope, the number of points of contact can be maximized to reduce the forces on each individual point. Although increasing mica thickness would appear to be a step toward improvement, Holland [11] found that thicker micas produce more gas under vibration and shock.

Since micas serve as insulators as well as supports and spacers, attention must be given to this function. Clean,

new mica is an excellent insulator, but evaporated metal films eventually form on the mica surfaces to present leakage paths. Although this cannot be completely avoided, certain steps can be taken to minimize the effect. For one thing, slits can be cut in the micas in a fashion which will not seriously impair the strength but will impose longer leakage paths between electrodes. Another procedure is to coat the micas with a rough insulating material to again provide longer paths. Finally, micas which do not have contact with more than one electrode may be installed as shields to keep particularly heavy concentrations of evaporated metal, such as flash getters, confined to areas where they will not affect insulating micas.

A worthy solution to many mica troubles is the replacement of mica by ceramic wafers. Ceramics are very strong, gas free, excellent insulators, and the same anti-leakage measures can be applied to them. However, ceramics are more expensive and they are not adaptable to the "press fit" assembly techniques.

Next to be discussed are the electrodes. As stated before, the electrode materials must be free of harmful elements. The designer must select materials with good electrical properties and good mechanical properties. The electrical problem is quite simple, but mechanically there are many factors to consider for each electrode. First consider the anode. It must be strong but not massive enough to make its inertia cause too much reaction to acceleration. The anode must be

restricted in its movements, and too much mass will cause its natural resonant frequency (of motion relative to its supports) to fall within the range of vibrations encountered in service. The anode must also radiate most of the heat within a glass tube, so its surface properties must be considered. For this purpose, anodes are frequently coated with carbon to make them good radiators. In some tubes the anodes are made entirely of carbon, but this practice is usually reserved for high power tubes, not receiving types. The limitations on anode temperature are the melting point and vapor pressure of the anode material, but the limitations of the envelope are usually reached before the anode limitations are. That is, the envelope may run too hot while the anode is in a safe condition. Most glasses used in tube envelope construction have rather poor heat transmission characteristics in the far infra-red region. For instance, soda-lime glass, which is very commonly used in receiving tube construction, will transmit about 90% of all incident radiation (for one millimeter thickness) in the visible spectrum and up to wavelengths of about two microns. But at 4.5 microns, the transmission drops to only 20% because the absorption curve rises steeply beyond two micron wavelength. A black body at 1,000°K radiates with the maximum of the spectral distribution of energy at about 2.88 microns. This is at a relatively steep part of the absorption curve. The tube designer may achieve cooler envelope temperature by using a molybdenum or tantalum anode, designed to

run at high temperature. A given value of power can be dissipated by the plate with a cooler envelope simply by decreasing the radiated wavelength [27]. This presumes a good heat absorbing surface surrounding the tube.

Next we look at the grids. Grids are inherently delicate structures since they must be essentially transparent to electron flow. The usual form is a fine wire wound around a pair of upright support rods. The wire is fastened by some means to the rods, and its own stiffness holds it in proper shape and position relative to cathode, anode, and other grids. This makes each half turn of grid wire a small thin bar rigidly fixed at its ends. This structure has a relatively low fundamental frequency and many other modes of vibration within the vibration ranges experienced in mobile environments, and if not carefully designed to bring the natural frequencies above the service vibration range, the grid can cause microphonic interference, the materials may fatigue and break, or actual short circuits may develop under severe conditions. The natural frequencies can be raised by choosing as stiff a material as possible, reducing the distance a wire must span unsupported (possibly by additional support rods or tie bars), and by using the lightest material consistent with adequate strength.

The grid support rods in most vacuum tubes present an important vibration problem too. They are relatively long and heavily loaded, and they have small cross-section. These

qualities make grid rods very likely candidates for low natural resonance frequencies. The resonance vibrations in this case are particularly serious because they tend to be of high amplitude, and by moving the entire grid structure they can modulate the electron stream effectively.

The same measures suggested for the grid wires can be applied to the support rods, i.e., short members, stiff materials, etc. In addition, Rowe and Welch [16] suggest rigid clamping of the rod ends by means of double micas as shown in figure (2). This effect is also obtained to a lesser extent by anchoring the grids with large grommets, to which the rods are welded. Another means of raising the natural resonant frequencies is to use shapes other than round rods for the grid supports. Small tubing or channel shapes have much higher frequencies of vibration for their weight than solid rods. Tubing or channel shapes would be slightly more expensive, but they are advantageous for purposes of locking to micas in that they are easily pinched. This method of locking is widely used for cathode sleeves. See figure (3).

In the mechanical design of electrodes, the effect of bake-out on the materials must be considered. Handley and Welch [10] experimentally determined the data given in Table (1) for Young's Modulus of various materials used in tube construction. It was noted that Young's Modulus was unaffected by additional bake-out periods. The reader is referred to [10] and [16] for formulae and other data useful in the de-

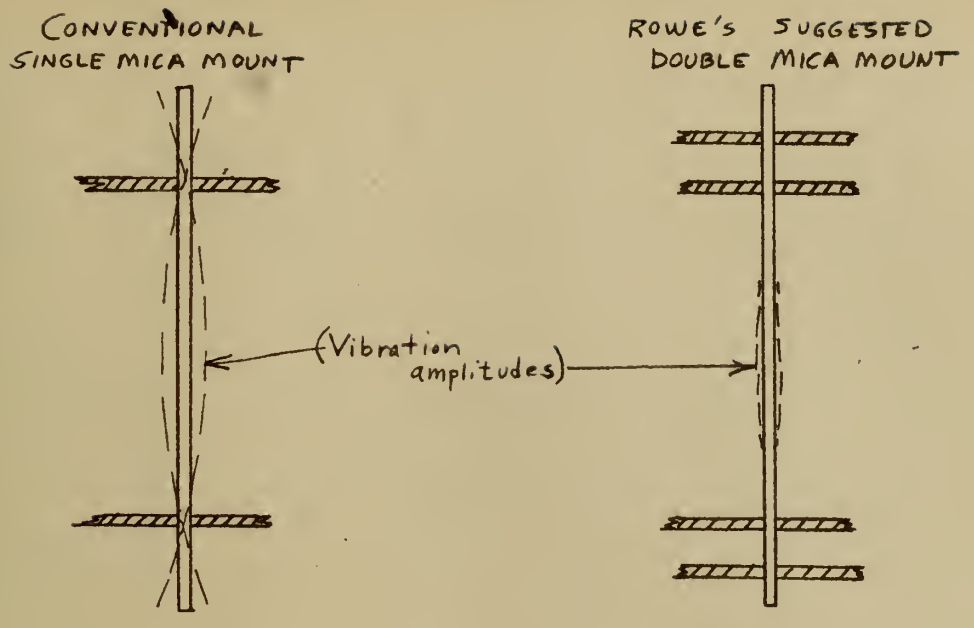

FIGURE 2, GRID SUPPORT ROD MOUNTS

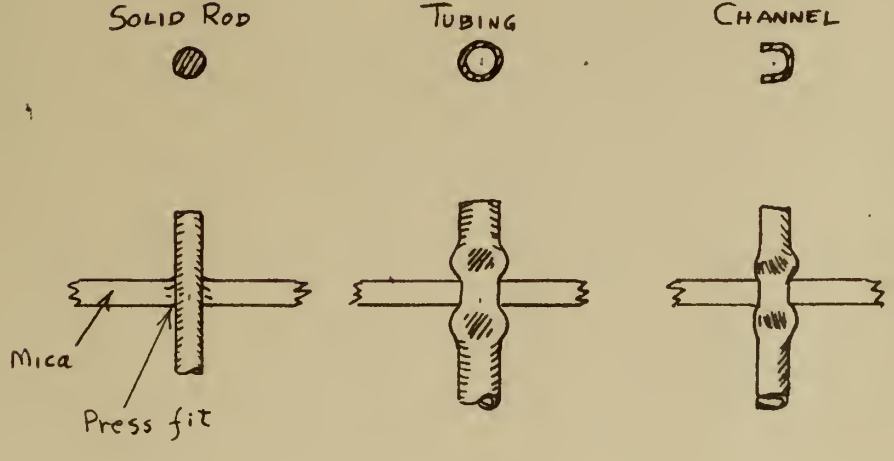

FIGURE 3 GRID SUPPORT ROD SHAPES and LOCKING METHODS.

Table 1. Changes in Young's Modulus due to bake-out.

Material	Mean Value of Young's Modulus ($dynes/cm^2 \times 10^{-11}$)	
	Before bake-out	After bake-out
Nickel	19.90	19.90
Copper	10.69	14.09
5% Chrome-Copper	10.70	14.18
Manganese-Nickel	22.3	22.3
Tungsten	34.15	34.15
Molybdenum	34.15	34.15
Mild Steel	21.20	21.20

sign of electrodes with high resonant frequencies.

There are also thermal and electrical properties of grids which must be acceptable. It is desirable that grids have high melting points, low vapor pressure, and high work functions. The service conditions for which a tube is designed will determine the importance of these characteristics. The high work function is necessary to minimize grid secondary emission. A common means of doing this is to plate the grids with gold. This gives the desired high work function and still allows the designer latitude in selecting a base metal with proper characteristics. In receiving types, the temperature problem in grids is not severe. Only tubes which dissipate grid power require special attention to the thermal properties of the grids. In these cases tungsten, molybdenum, or tantalum may be used, and these metals have the combination of high melting points and high work functions.

The third electrode to be considered is the cathode. Usually the cathode is a nickel tube, round or oblong in cross-section, coated with appropriate emissive materials. The metal sleeve is most critical in its chemistry. Impurities will quickly render a cathode useless by poisoning the coating or contributing to other faults such as interface. The cathode core (or sleeve) material must satisfy the following demands:

(1) It must be stable at manufacturing and operating temperatures, in particular it must have a low rate of evaporation and a high melting point.

(2) It must have a favorable influence on the emission of the oxide coating.

(3) It must be chemically stable toward the oxide coating at all temperatures encountered.

(4) It must be readily degassed in manufacture.

(5) It must have good thermal properties, such as low heat conduction and low radiant emission.

(6) It must have low recrystallization.

According to Wagener [19], nickel is the only practical material which can satisfy all these conditions. In the case of a directly heated oxide cathode, wherein the oxide is bonded to a heated wire, then another requirement must be added to the list, namely high tensile strength at high temperatures. Directly heated cathodes are usually mounted under tension in order to keep interelectrode distances fixed. Since nickel is not strong enough, tungsten is used under tension conditions. Thus the practical cathode core materials are narrowed to only nickel and tungsten. Tungsten has the unfavorable property of reacting with the alkaline earths in the oxide coating, and therefore it is slightly inferior to nickel when the effect of core material on emission is considered. The reaction with the alkaline earths (barium and strontium oxides) produces an interface layer. Some grades of nickel are high in silicon content, and this also results in the formation of interface, as previously discussed.

Cathode sleeves are generally fabricated in two ways.

The sleeves are either extruded seamless shapes or they are rolled and folded at a seam. The extruded shape is more expensive, but it is best for reliability because the folded type frequently traps some foreign material, causing the oxides to flake off along the seam.

A late and most promising development in cathodes is the "sintered" or "molded" cathode which is under study at the BELL TELEPHONE LABORATORIES [13]. This cathode is not oxide coated, but its emission is almost as high as an oxide-coated cathode for a given amount of heater power. Many techniques of manufacture are being investigated, but the general theory of the sintered cathode is as follows. Pure nickel is powdered and mixed with the usual active cathode materials, namely barium and strontium carbonates, and an organic binder is added. The mixture is formed in the desired shape by means of a die under great pressure. The pressed nickel shape is then sintered in a furnace to a point where the nickel grains fuze. This results in a sort of matrix of nickel particles, each coated with active emitting material. The shape is strong and can be machined like a solid piece of metal. Experiments have shown these cathodes to be extremely resistant to the factors which ruin conventional oxide-coated-cathodes. These cathodes have been exposed to atmospheric air pressure, at room temperature and at operating temperature, with no apparent effect on their activity. Currents greater than ten amp/cm^2 have been drawn for brief periods at 950°C to 1,000°C

with no ill effects. Life periods up to 5,000 hours are obtained with current densities of 500 milliamperes per square centimeter at 500 volts anode potential. Life tests at 1,200 volts have given similar results. This type of cathode is presently under intense investigation by many commercial organizations, and if it advances to general use with capabilities as good as those demonstrated experimentally, vacuum tube reliability will have made a great gain.

There are other new types of cathodes which are related to the "molded" cathode in the sense that they have fuzed matrix structures which seem to dispense barium to the emitting surface. One is the Lemmens[1] or "L" cathode which uses a porous tungsten plug, one side of which is coated with barium-strontium oxide. The oxides provide barium which migrates through the tungsten and emits in a manner similar to a film on the other side of the tungsten plug. The "L" cathode is a durable, high current density, source of emission, and it is the subject of considerable interest in the industry, as are a number of similar new cathode ideas.

The majority of the receiving tube types use the indirectly heated cathode sleeve, and a tubular structure is inherently rigid, so vibration and shock present no problem as far as transverse vibrations are concerned. Filamentary cathodes, however, are definitely influenced by these conditions. Fil-

1. Lemmens, Jansen, and Loosjes; PHILIPS TECHNICAL REVIEW, Vol.11, 1950, Pg. 305.

amentary cathodes behave as stretched strings when subjected to accelerations. Since the metal must expand when heated to operating temperatures, it is very difficult to maintain high tension and thus keep vibration amplitudes low. In general, directly heated filamentary cathodes are not practical for reliable, rugged tubes. For a treatment of vacuum tube filament motion under shock, see reference [18].

The heaters in indirectly heated cathode tubes are a major reliability problem. Heater failures are short circuits or low leakage paths to the cathode, or open circuited heater wires. The leakage to the cathode is the result of failure of heater insulation. Heater wires are either helically wound or simply folded up, then inserted into the cathode sleeve. The insulation is a hard, vitreous, coating baked on the wires. Aluminum oxide is most often used for this purpose. The wires are dipped or sprayed to coat them with a suspension of this material. Then the wires are dried at several hundred degrees centigrade and finally they are flashed at about 1,500°C to vitrify the coating. Such coatings have sufficiently high mechanical strength and electrical strength to make them satisfactory for most receiving tube applications. For high reliability the process is modified slightly in that the coating is applied in a succession of thin layers, each baked individually. Further, after bending (in the folded type) the bends are retreated to guard against cracks and peeling. The bends themselves are usually the failure points in

heaters, and for this reason they must be made very carefully. If the radius of curvature is kept above a certain minimum value the bends will be sufficiently strong. Manufacturers particularly concerned with reliability inspect all heater wire bends microscopically to ascertain that they are made properly.

There is conflict in the literature as to the overall reliability of folded heaters. U.S. manufacturers are using folded heaters in many designs and feel that proper care in fabrication will provide the necessary reliability level. Certain British researchers have concluded that the helical heater is the solution to heater failure problems. E.G. Rowe [15] reported in 1952 that his organization in Great Britain experimented with folded heaters by making them of heavier wire (also longer) which aided a great deal in reducing "rattle noise" because of a tighter fit, but they still showed the bends to be weak points. They moved to helical heaters made of heavy wire. This eliminated the bends and thereby eliminated breaks in the wire under vibration conditions. The helices are easy to insert, fit snugly, and do not cause rattle noise. They also operate at lower core temperature which promotes long life.

The reverse helical heaters are definitely superior for reliable tube design in the opinion of this writer. The helix has almost no motion relative to the cathode sleeve, and this preserves the heater insulation properties to prevent leak-

ages. Since tungsen maintains good mechanical properties at operating temperature, its natural elasticity can be used to keep it snug within its sleeve. Also, the cathode temperature can be kept constant over its entire length by decreasing the helix pitch near the ends or other heat conduction points along the cathode sleeve. Heat flow from the sleeve to outside heat sinks can be calculated with reasonable accuracy to permit design of the helix to counteract the effects of the heat flow. The folded heater cannot be readily made to accomplish this compensation for conduction loss. See figure (4).

The matter of maintaining even cathode temperature is very important because deviations both above and below optimum cause abnormal deterioration of emission. If temperature is too high, the barium will vaporize too quickly and the emitting surface will become barium deficient. This excess of evaporated barium will cause interelectrode leakages or secondary emission elsewhere within the tube, as mentioned earlier. Low cathode temperature reduces current capacity, hence lowers transconductance, and it makes the cathode more susceptible to ion damage and poisoning.

The vacuum tube industry devotes quite a bit of effort to research on heaters for indirectly heated cathodes. At present, tungsten, tantalum, and molybdenum are the best materials for heaters. Heater material must be mechanically sturdy at very high temperatures, on the order of 1,200°C to

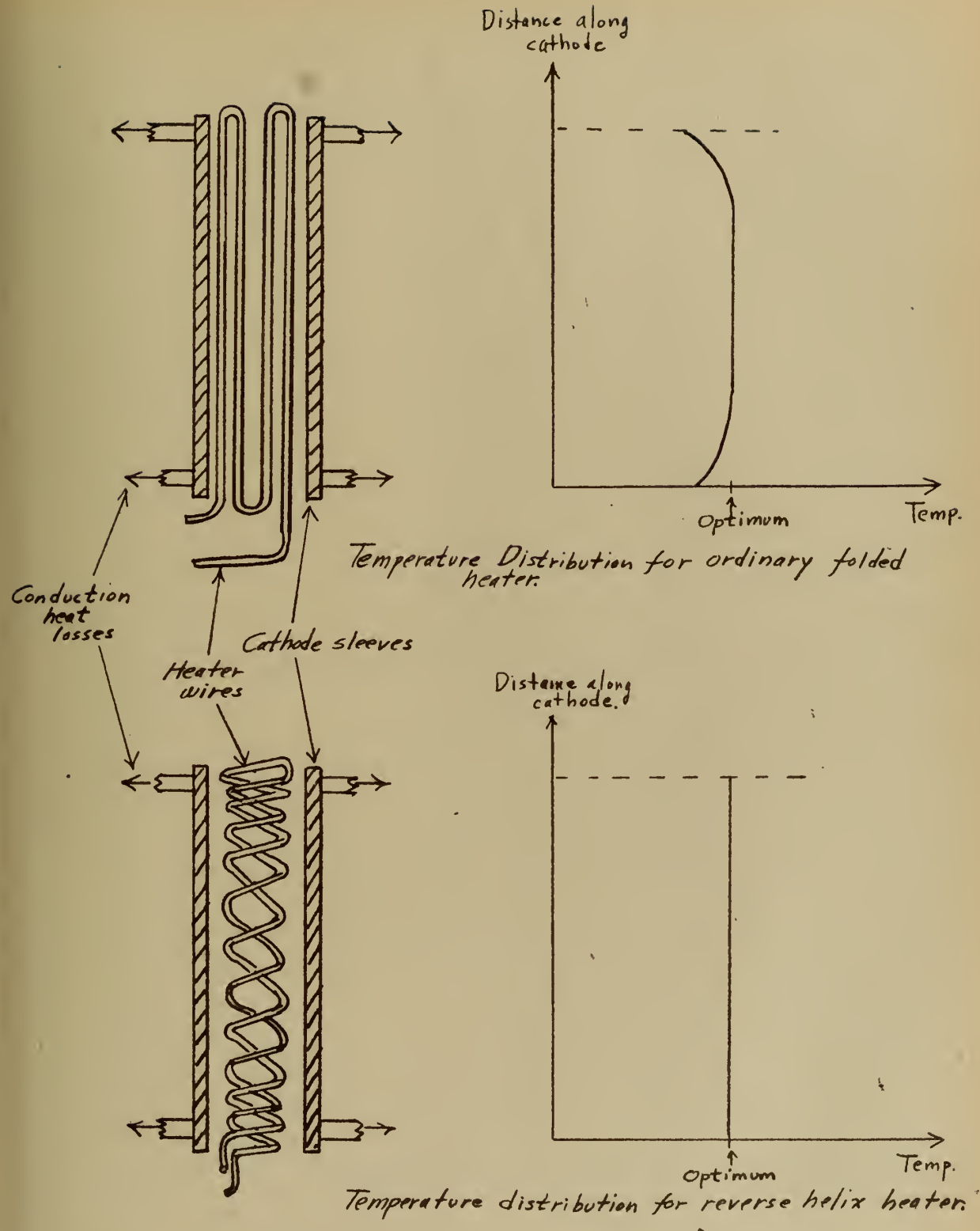

FIGURE 4. Temperature Distribution on Cathodes

1,300°C, and it must have reasonable resistivity in order to dissipate the required heat. Though tungsten is the best material, the tube designer is restricted because of its resistivity. In order to make a heater rugged, one would like to make it of heavy wire, but this decreases its resistance per unit length so it must be made longer. Since the available space for the heater is small, the limit of this process is quickly reached. All the designer can do is use the heater space to best advantage by making the heater as thick and as long as he can and still get it into the sleeve.

The remaining inherent weakness in heaters is the connection between the ends of the heater wires and the tube lead-outs. Usually this is a spot-weld connection because it is the only practical method. The spot welds are a problem because they make the heater wire brittle in the vicinity of the weld. Brazing has been used, but it is generally unsuccessful because the brazing materials tend to vaporize when the heater runs at operating temperature. A continuous wire is manifestly impractical for many reasons. Therefore the spot-weld method must be accepted until a better device is developed. However, the RADIO CORPORATION OF AMERICA uses a technique which eases the problem considerably. In certain tubes, RCA places a metal sleeve over the spot-weld and crimps it above the weld to the heater and below the weld to the lead-out wire. This provides an auxiliary electrical connection and a splint effect to prevent flexure in the brittle area of

the weld.

The BENDIX AVIATION CORPORATION has had success in improving heater reliability by the use of an extruded aluminum oxide insulator within the cathode sleeve. A hairpin type heater coil is inserted into this insulator. This solid insulating body between heater and cathode has virtually eliminated heater-cathode shorts in the tubes which have it. BENDIX has also developed a new method of connecting the heater wires to the stem leads. The tungsten wire is covered with a nickel sleeve so that the actual weld is made from nickel to nickel with the tungsten heater forged in between.

There are a number of steps which can be taken external to vacuum tubes to improve their reliability, and it is fitting that some of these measures be discussed at this point. Of course it would help to eliminate or diminish the environmental conditions which contribute to poor performance, and any means possible to do so should be implemented. When these means have been exploited to their limits, then an effort should be made to protect the tubes from the remaining necessary evils of shock, vibration, and temperature.

Shock mounts and cooling systems must be designed according to the environmental conditions to be neutralized. In addition to these measures, operation and maintenance procedures can be aimed toward improvement of tube reliability. Heater life can be extended if on-off cycling is minimized, and it can be further extended if heater voltages are applied grad-

ually rather than suddenly [12].

From the maintenance standpoint, it would be well to adopt the "marginal performance" method of testing which is mentioned later in this paper. Wholesale replacement of tubes on a periodic basis has not shown itself to provide increased equipment reliability. Tube failures in operation follow a logarithmic pattern in which failure rates are highest when tubes are new, and the failure rates decrease according to a logarithmic curve. The wholesale periodic replacement neither eliminates early failures nor obtains the benefit of the better tubes with long useful lives ahead of them.

CHAPTER V

PROGRESS IN DEVELOPMENT OF RELIABLE TUBES

When World War II commenced, commercial vacuum tube technology was geared to the home entertainment radio market. Tubes were produced as economically as possible to give reasonable life in the relatively comfortable atmosphere of home radios. These types were the only ones available for the sudden enormous demands of the armed forces. Special types (electrically) were quickly produced for the varied needs of the military, but the basic design and construction methods were those which had been employed for ordinary commercial market tubes. The rigors of military service soon demonstrated the need for improvement, and one of the earliest steps in this direction was the Navy's "W" program to make tubes more rugged. This was prompted by the heavy failure rate under gunfire shock conditions. The Bureaus of Aeronautics and Ordnance requested remedial action be taken by the Bureau of Ships, and in 1943, BuShips and the Naval Research Laboratory wrote specifications for improvement. Under these specifications the existing JAN requirements were to be met, but additional specific requirements regarding vibration endurance, structural resonances, and resistance to shock damage were included. Working in this program, SYLVANIA ELECTRIC PRODUCTS, INC., with assistance from NRL, built the 6L6WGA to replace the 6L6GA. The 6L6WGA was short and sturdy, used grommets in the micas, had side rods

welded directly to stem leads, and used positive stops on the grid support rods. The "W" program also sponsored a RADIO CORPORATION OF AMERICA project on "ruggedizing" the 6AC7. CHATHAM ELECTRONICS CORPORATION ruggedized a 2050, a 6H6GT, and a 6AL5 under Navy contract. These tubes were strengthened versions of existing types. The lessons learned were the basis for further refinements to promote reliability and long life. After the war, advances which had been made in industrial electronics created a further demand for better tubes. The aviation industry made the first major commercial step by contracting with AERONAUTICAL RADIO, INCORPORATED, to investigate their reliability problems in airborne equipment. ARINC organized close liaison between the manufacturers and the airlines. Defective tubes were returned to manufacturers and they were carefully examined to determine faults and allow corrective measures to be executed. Continued liaison enabled the manufacturers to keep track of their progress, and eventually substantial improvements were made. A "selection" process was tried by ARINC as an interim measure. This process consisted of obtaining a large number of stock tubes, establishing very rigid acceptance standards, and then culling out those tubes which could not meet the standards. This was expected to yield a certain percentage of highly reliable tubes. The 6AK5 was the worst offender in the airline industry, so ARINC obtained 2,000 new 6AK5's to screen. Only 60 tubes passed all the tests, but those 60 performed no better statistically than

tubes picked at random, so the selection process was dropped. It should be mentioned here that British researchers report excellent success with this method. It may be that the 6AK5 was an unfortunate choice for the "selection" experiment. The actual improvement program on the 6AK5, conducted by the GENERAL ELECTRIC CO., resulted in the development of the 5654. After three years of effort, the failure percentage within the first thousand hours service was reduced from 30% for the 6AK5 to 3.2% for the 5654. It is estimated that the airlines saved $250,000 in the year 1949 alone as a result of using this improved version of the 6AK5. Other benefits were improved air safety and fewer flight delays.

Ten miniature types were selected for improvement under this program. Results of the earlier "W" program were employed and heaters were improved. The aims of the project were primarily reliability, and secondarily, long life. The most important demand was high dependability for a definite period.

In 1951, the Bureau of Ships awarded a contract to ARINC to conduct a program similar to the airlines program for the Navy. It was handled much the same way. ARINC arranged for defective tubes to be sent from all applications - aircraft, ships, and shore stations - to certain testing facilities. Some of the results of this project were recently published by Mr. Joseph R. Garafola of ARINC [77]. About 100,000 tubes were received for examination, and they were grouped as follows:

(a) Catastrophic failures. Due to shorts, mechanical failures, breakage, etc.

(b) Gradual deterioration. Decay of transconductance, leakage build-up, etc.

(c) No defects. Some tubes in this class had microphonics or noise which could not be readily tested, but most tubes had simply been removed from service before they could deteriorate beyond acceptable limits.

Of the 100,000 tubes analyzed, the defect percentages were as follows:

(a) Catastrophic	37.6%
(b) Gradual deterioration	27.0%
(c) No defects	35.4%

The catastrophic failures are being efficiently countered by many manufacturing companies. It is a matter of quality and good design. "Ruggedization" describes the remedy very well, and the need for it has been recognized for quite a few years.

Gradual deterioration has been neglected until recently. It amounts to decay of transconductance and appearance of leakages. The causes of decay of transconductance are gas and interface, while leakages are caused by deposits of conducting material on insulators and glass electrolysis. These factors

were discussed in detail earlier in this paper.

Cathode interface was found most frequently in tubes operated for long periods of time, particularly in cases where cathode current was very small or zero. ARINC found interface distributed among 2600 tubes as follows:

51% of tubes removed from aircraft.

70% of tubes removed from ships.

91% of tubes removed from shore establishments.

These figures progress in the same manner as tube hours for the three cases.

All these causes of gradual deterioration can conceivably be handled by good design, enlightened cathode chemistry, and proper operating conditions.

The third defect class, "no defects", must be remedied by improved electronics maintenance programs. Fully 35% of the 100,000 tubes could have been used satisfactorily. A maintenance system must be devised wherein tubes can be used to their maximum satisfactory service point, yet permit replacement before failure or deterioration below mimimum limits. Properly handled, such a program would cause less abuse by handling and thereby cut down the catastrophic failures. The "marginal testing" system has been used in large electronic computer systems. One way of using marginal testing is to lower the heater voltages and thereby decrease transconductance momentarily. The drop in performance or output of the circuit involved should be predictable, and if the drop is excessive

it is time to test and replace the tubes which have deteriorated too far. This type of testing must be a built-in feature of an equipment, and it should be more elaborate than simply lowering heater voltages.

At present, commercial airlines obtain far more useful service from their improved types than the military services get from unimproved types. ARINC attributes this better tube life to the following factors:

(a) Better tubes

(b) Less rigorous use

(c) Less complexity in equipment

(d) Difference in maintenance systems

The last reason given, difference in maintenance systems, means the airlines test for equipment performance whereas the military maintenance personnel lean to wholesale tube swapping, and they rely heavily on tube-tester results, which are not always conclusive.

ARINC estimates that with improved tubes as they can be built today, it should be possible to obtain a tube removal rate as low as 0.1% for the first thousand hours.

Another phase of reliable tube development currently in progress is the research study of causes of tube failure being conducted at Cornell University. The school of Electrical Engineering receives large numbers of defective tubes, analyzes them, makes recommendations, and distributes reports of their work. Manufacturers concerned with tube reliability re-

ceive these reports and in this way the fruits of research are most effectively distributed.

As an example of this work, technical report No. 2 dealt with the following tube types: 6AG7, 6AK5, 6AR6, 6C4, 6J6, 6SN7GT, and 12AU7. This report lists the most significant failure causes as follows:

(1) Glass troubles in miniature tubes

(2) Short circuits in close-spaced tubes

(3) Life deterioration in all tubes

(4) Serious misapplication

In the miniature types, Cornell suggests much glass trouble can be eliminated by the following precautions:

(a) Wire tube sockets with tubes in place in order to keep socket springs in correct alignment.

(b) Handle tube shields carefully to avoid striking sealing tips on tubes.

(c) Insure that springs contained in shields do not have sharp ends which may scratch the tube envelopes.

(d) Use tube pin straighteners on new tubes.

To avoid shorts and improve tube life, tubes which have had early failures eliminated should be used. This refers to "reliable" types as presently manufactured by many companies. All "reliable" tubes are operated for a certain period at the factory, usually about 50 hours, to weed out early failures. It has been conclusively shown that most tube failures occur very early in life, and, therefore, tubes surviving fifty

hours have a high probability of long life.

Cornell also discovered numerous instances of misapplication causing short life. Many tubes are abused by operating above rated values. This can only be remedied at the equipment design stage.

The effort to investigate failure causes and improve vacuum tubes is presently being carried on by many groups. All tube manufacturers are interested in the problem, and their work is sponsored by their own financing as well as by contract from the armed forces and commercial interests. The RADIO CORPORATION OF AMERICA has developed its "special red" line of tubes primarily for the industrial market. GENERAL ELECTRIC CO. distributes their "five star" tubes which are a series of high reliability tubes. SYLVANIA, RAYTHEON, and other companies manufacture "premium" versions of existing tube prototypes. SYLVANIA ELECTRIC PRODUCTS, INC., has developed a new concept in vacuum tubes in their "stacked" ceramic model. It has an all ceramic envelope and the tube elements themselves are stacked ceramic and metal parts. This tube is not yet in production and details are not available.

The author had the privilege of working with EITEL-MCCULLOUGH, INC., for several months and assisting in their development of another all metal and ceramic tube which shows great promise for a high degree of reliability. This tube, designated CD-8, is a twin triode which is ideally suited to automatic production because it is truly a stacked tube. All

the parts are simple and rugged. See figure (5) for an exploded view of this tube. The elements of the CD-8 have natural resonances whose fundamental frequencies are at least several kilocycles, and no high amplitude resonances are below four kilocycles. Prolonged vibration tests at the known resonance frequencies have thus far failed to produce failures. Under test for microphonisms, the only significant outputs occur above 4,000 cycles per second. Ordinary receiving types have major microphonic responses starting at about 40 cycles and going on up to kilocycles [8,16].

The CD-8 has been mechanically designed for installation as a permanently connected component; that is, it will not be readily removable. See figure (6). These tubes are intended to be pumped to hard vacuum, at least 3×10^{-7} mm mercury, and the natural pumping action of the tube will bring them down to the 10^{-10}mm region. Since the tube can be thoroughly outgassed by high temperature bake-out and the parts are simple enough to make extreme cleanliness practical, it is expected that very long life will be achieved. The tube is assembled by simply stacking the pieces in order with brazing material sandwiched between pieces, then pumping, baking, activating, brazing, and cooling in a vacuum chamber. The completed tube is then removed from the vacuum chamber and aged in a test rack for a certain period.

This procedure is presently being followed at EITEL-McCULLOUGH on a laboratory basis. Several hundred tubes have

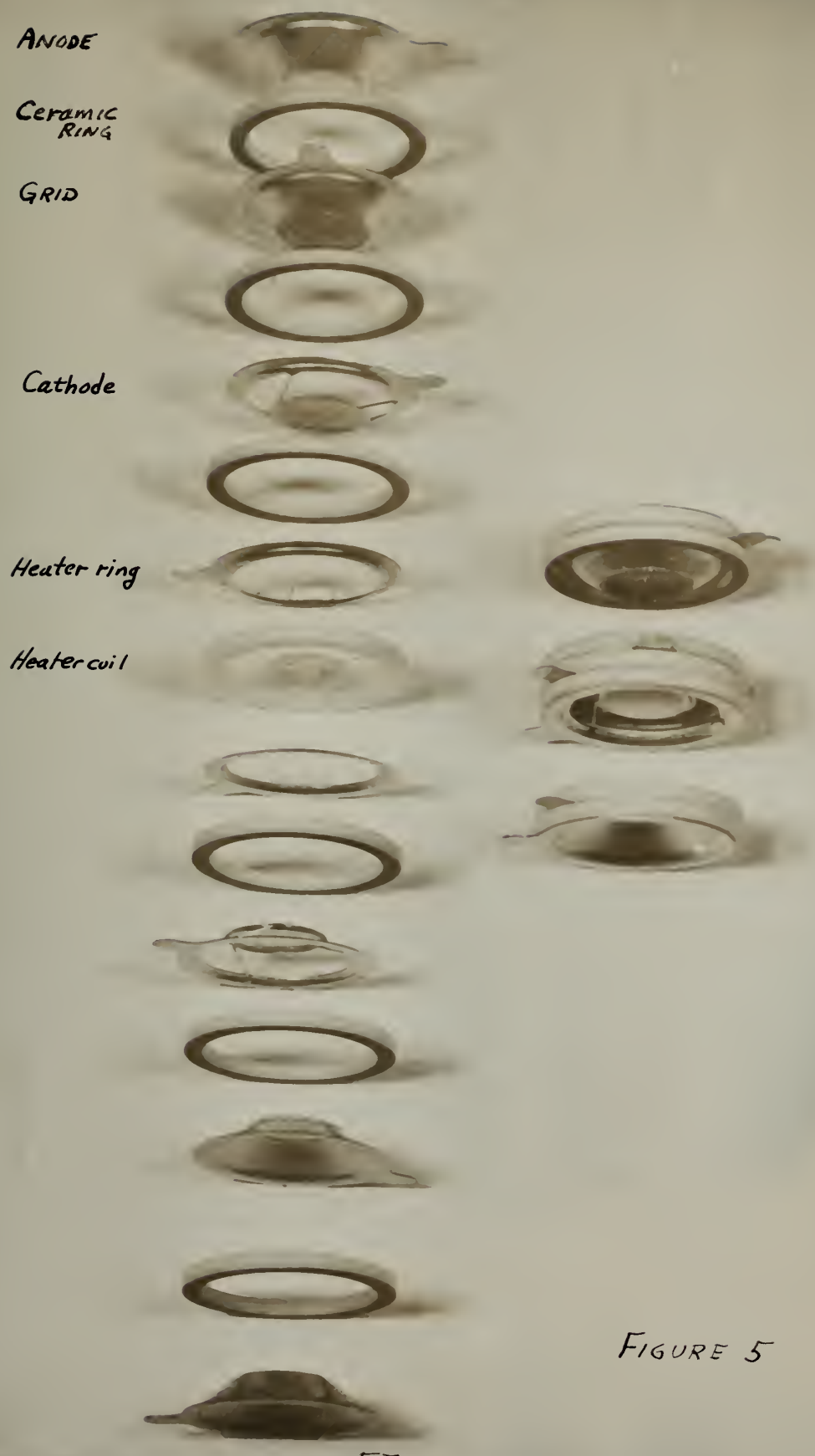

FIGURE 5

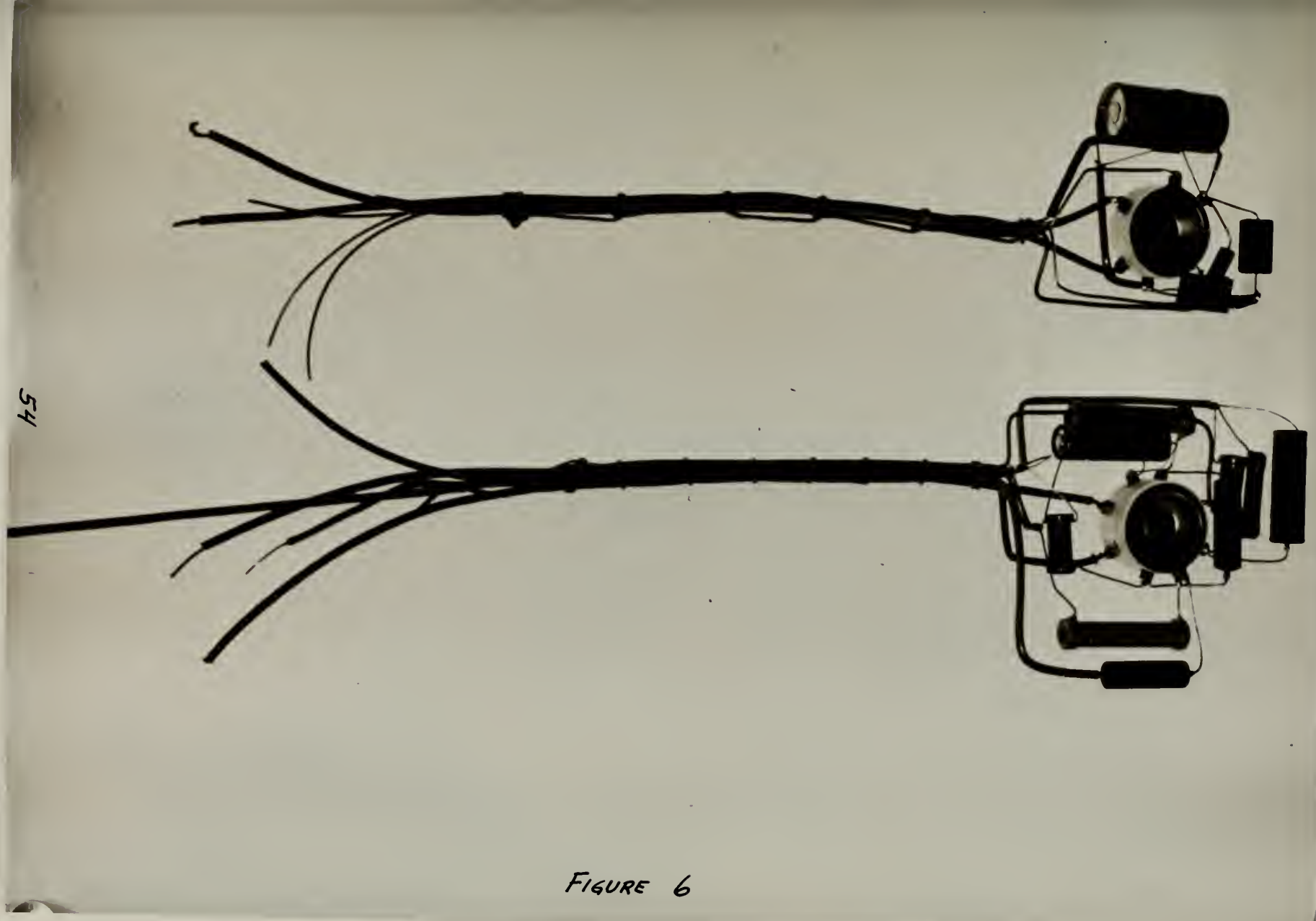

FIGURE 6

been built and the results are very encouraging. In the CD-8, EIMAC has used very few spot welds. These are on the heater connections and cathode support struts. The heater wire is of relatively large diameter and its movement is so restricted that spot weld failures will be no problem. The tube is almost immune to overload failure. The only such failure so far produced has been melting of the grid mesh with grid dissipation power of about five watts. It is expected that the grids will safely allow grid dissipation of several watts in service if desired.

Figure (7) demonstrates some of the steps in the evolution of a reliable twin triode. The 6SN7 is shown although the EIMAC CD-8 differs somewhat in electrical characteristics from the 6SN7. Figure (7)a shows a typical commercial market 6SN7. It uses a "pinch" stem, relies on mica pressure on the bulb to provide support, and the structure is relatively tall. The 6SN7 in figure (7)b is a "W" version. It has been shortened to add strength and the micas have been provided with springs to prevent actual glass to mica contact with the consequent ill effects. Support rods have spot-welded clips at the micas, and grommets have been used at some other mica holes to avoid rattle and splitting. The lower mica spacer utilizes the "slotting" technique to lengthen grid-cathode leakage paths, and all micas are coated with a roughening material, probably aluminum oxide. The tube also uses a large amount of getter material, originally contained as a pellet

a. Raytheon
6SN7 GTA

b. Sylvania
6SN7 W GT

c. RCA
5902

d. EIMAC
CD-8

FIGURE 7

within the folded metal shield seen at the top of the electrode structure. The tube envelope is mirrored over about half its length with barium deposit. In figure (7)c is shown the RCA "special red" 5692, which is a 6SN7 replacement in every respect except for slightly higher heater current. This tube has a very rigid electrode structure, employing five heavy vertical support rods, all of which are bonded to mica insulators with grommets. Two getters are employed and a special mica disc is installed to shield insulating surfaces from getter material. The heater wires have sleeves to provide reliable connection between heater and heater lead-ins. Cathode sleeves and grid side rods are all locked to micas mechanically to prevent longitudinal movement. A button stem and special non-hygroscopic base minimize leakages. Figure (7)d shows the EIMAC CD-8 in which most of the special features employed in the 6SN7W and 5692 are inapplicable.

This writer feels that the EIMAC ceramic CD-8 is the beginning of a new, expanding trend in the art of building vacuum tubes, and for this reason some history of its development seems in order.

EITEL-MCCULLOUGH, INC., contracted with the U.S. Air Force to produce a reliable electrical counterpart of the 6SN7, using only ceramic and metal parts. The size, shape, socketing, etc., were not specified because it was desired that the contractor should not be held to the superficial characteristics of conventional tubes. EIMAC engineers felt that conventional tubes were

clinging to the "light-bulb" configuration in which the Edison effect was first discovered, and they attempted to clear their minds of what had been done and start over. The idea of simple, planar elements seemed advantageous and was adopted. From here many designs were tried and discarded for various reasons, mostly difficulty of manufacture. Small holes in ceramic pieces were present in all the early designs, and eventually the holes had to be ruled out. Firstly; small, accurate holes are difficult to make in ceramic material. Only diamond drills or super-sonic drills can make them. Secondly, the holes eventually introduce stresses and precipitate cracks. Finally, the holes do not present good automatic production possibilities. So, the present stacked design, CD-8, was developed and adopted, having none of the troublesome small holes. The characteristics initially obtained were superior to the 6SN7, so the contract was amended to release EIMAC from duplicating the 6SN7 electrically. This writers contribution to the CD-8 was in making calculations on tube parameters and capacitances, and in making tests on the tubes. The tests were to determine natural resonance frequencies, microphonic properties, vibration endurance, and electrical parameters. The tests to determine resonance frequencies were made on an electromagnetic transducer which provided sinusoidal vibration in one direction from about 10 cycles/sec to about 5,000 cycles/sec. At the low frequencies, accelerations were limited because peak amplitude displacement was about one inch. In the mid-range, accelerations up to 50 G

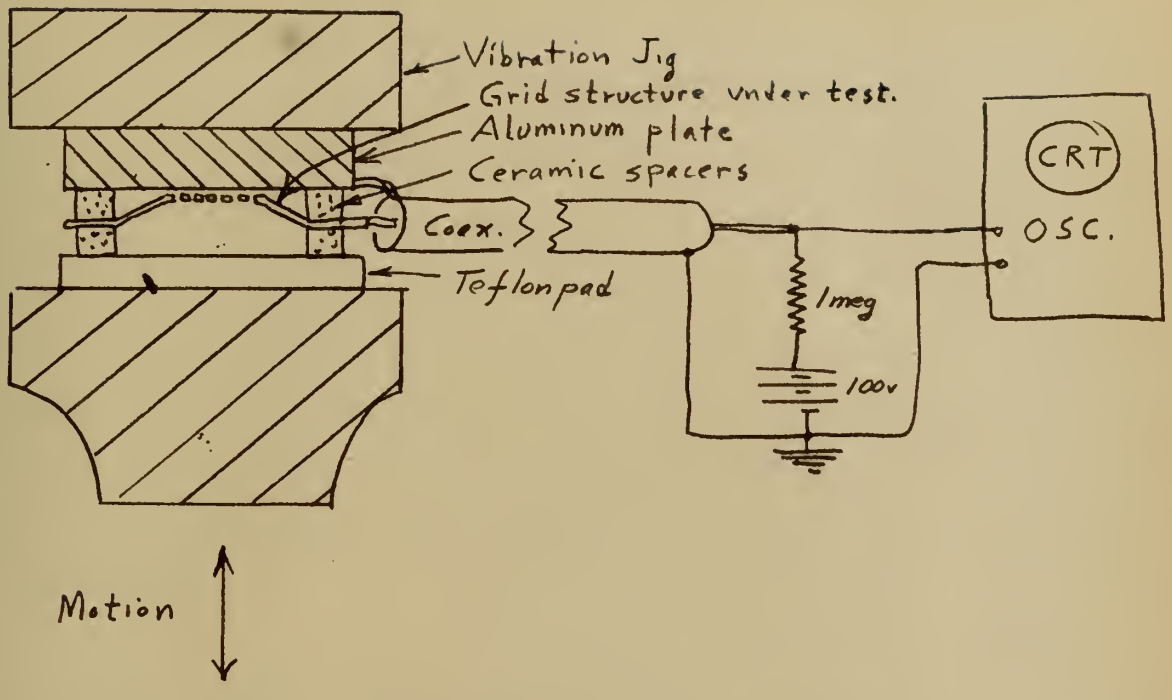

FIGURE 8 . Mechanical Resonance Tests

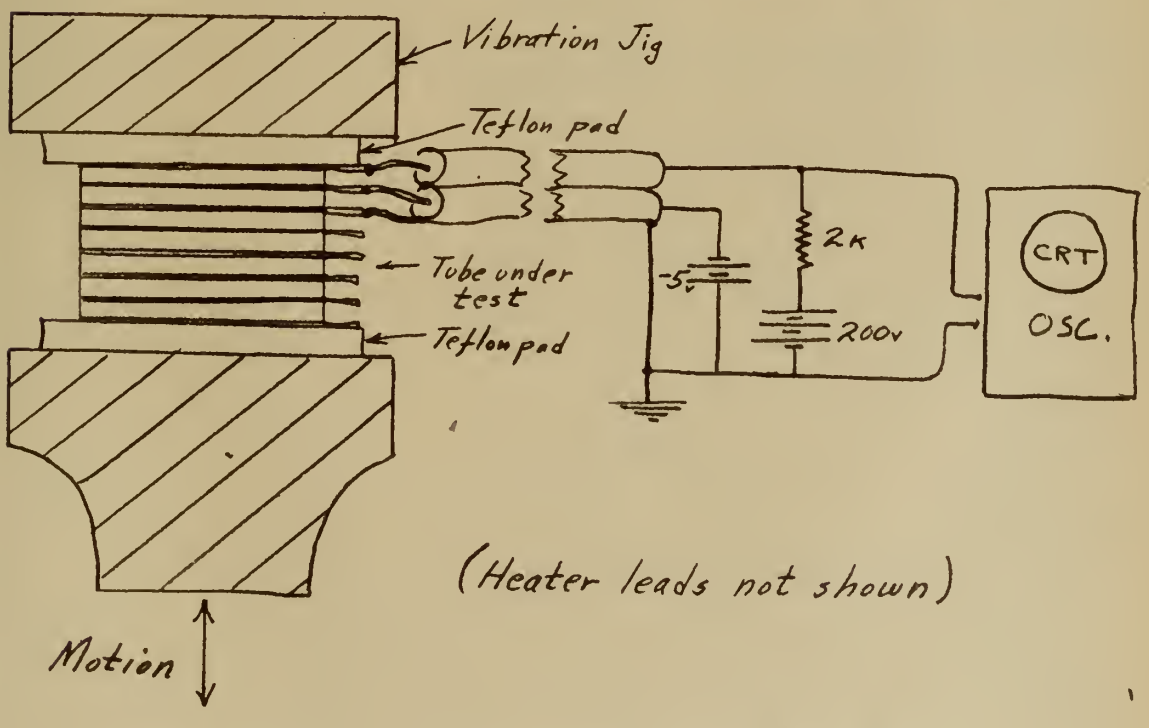

FIGURE 9 Microphonism Tests

could be obtained, and at 5,000 cycles/sec approximately 5 G acceleration was possible. In a special jig, designed to have no resonances below 5,000 cycles/sec, various sub-assemblies and individual parts were mounted and vibrated to determine their natural resonances. A condenser microphone type of technique was used to detect resonances. See figure (8). Frequency was slowly varied over the entire range of the equipment, and any natural resonances showed as high amplitude indications on the oscilloscope. This method was used to test grid, cathode, anode, and heaters. The results were as shown in Table (2).

Table 2. Mechanical Resonances in CD-8

Part	Frequency (cps)	Remarks
Anode	-	No resonances found below 10 Kc.
Cathode	3500	Low amplitude motion
	5000	" " "
Grid	4000	High amplitude motion
Heaters	0 - 600	Rattles within cathode cans

Several finished tubes were connected up as amplifiers, as outlined in JAN specifications, and tested for microphonism. Tubes were mounted in the vibration jig and vibrated at frequencies ranging from zero to 5,000 cycles. Set-up was as shown in figure (9). In these tests the only significant outputs were in the vicinity of 4,000 cycles/sec, result-

ing from grid motion. The output at 4,000 cycles/sec at one G was 0.15 volt. This does not approach the usual limits on microphonic output. Aside from the peak, the spectrum was very clean. Output was less than ten millivolts at five G for all frequencies below 4,000 cycles/sec.

In fatigue failure tests, grids, cathodes, and heaters were vibrated at high accelerations for extended periods and no failures were produced. Although the heaters do have motion relative to the cathode cans, no insulation leakages or heater failures occurred during several weeks of testing.

The electrical tests were made on all tubes. Plate characteristics curves were taken, and amplification factor, transconductance, and plate resistance were measured at certain operating conditions. Since each tube had a detailed history card, it was frequently possible to trace electrical abnormalities to a particular step of assembly.

At present the tube is very promising, and an improved version, smaller, lighter, and with better characteristics, is about to be constructed.

The author had a part in designing a new ceramic version of the 6AK5 which is now ready to leave the drawing boards for initial assembly. It is intended for ultimate automatic production, and it should be as reliable as the CD-8.

Other tubes in the standard EIMAC line have been modified to replace all glass with ceramic material, and this program is continuing.

In this paper, the author has attempted to summarize the progress of reliable tube development. A large number of papers and reports have been published on the subject, most of them dealing with the details of some particular phase of the problem. Many of the papers duplicate information found in other papers, and in some cases they conflict. In any case, it is difficult to obtain an overall picture from any single publication, and it is hoped that this paper has provided such a picture.

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APPENDIX I

TUBE TYPES FOR WHICH "RELIABLE" OR "PREMIUM" REPLACEMENTS HAVE BEEN DEVELOPED AND ARE CURRENTLY AVAILABLE

Prototype	Replacement	Description
6L7	1612	Pentagrid Mixer
6J7	1620	Sharp Cut-Off Pentode
6F6	1621	Power Amplifier Pentode
6L6	1622	Beam Power Amplifier
12SC7	1634	High-Mu Twin Triode
12L8-GT	1644	Twin Pentode Power Amp
6AK5	5591	Sharp Cut-Off R.F. Pentode
6AK5	5654	Sharp Cut-Off R.F. Pentode
2C51	5670	High-Frequency Twin Triode
7A6	5679	Twin Diode
	5686	Beam Power Amplifier
	5690	Full Wave Vacuum Rectifier
6SL7-GT	5691	High-Mu Twin Triode
6SN7-GT	5692	Medium-Mu Twin Triode
6SJ7	5693	Sharp Cut-Off Pentode
	5718	Medium-Mu Twin Triode
	5719	High-Mu Triode
6AS6	5725	Dual-Control R.F. Pentode
6AL5	5726	Twin Diode
2D21	5727	Thyratron
6K7	5732	Remote Cut-Off R.F. Pent.
6BA6	5749	Remote Cut-Off R.F. Pent.
6BE6	5750	Pentagrid Converter
12AX7	5751	High-Mu Twin Triode
	5797	Semi-Remote Cut-Off Pent.
	5798	Medium-Mu Twin Triode
12AU7	5814	Medium-Mu Twin Triode
25B6-G	5824	Beam Power Amplifier
6X5GT	5838	Full Wave Rectifier
6X5GT	5839	Full Wave Rectifier
	5840	Sharp Cut-Off R.F. Pentode
6X5GT	5852	Full Wave Rectifier
6V6-GT	5871	Beam Power Amplifier
6L6-G	5881	Beam Power Amplifier
	5896	High Frequency Twin Diode
5899	5899	Semi-Remote Cut-Off Pentode
	5902	Beam Power Amplifier
2A3	5930	Low-Mu Power Amplifier Tri.
5U4-G	5931	Full Wave High Vac. Rect.
6L6-G	5932	Beam Power Amplifier
6SA7	5961	Pentagrid Converter
6V6-GT	5992	Beam Power Amplifier
6X4	5993	Full Wave Rectifier

Prototype	Replacement	Description
6AQ5-W	6005	Beam Power Amplifier
6SG7	6006	Semi-Remote Cut-Off Pent.
6AK5	6028	Sharp Cut-Off R.F. Pentode
25L6-GT	6046	Beam Power Amplifier
12AX7	6057	High-Mu Twin Triode
6AL5	6058	Twin Diode
12AT7	6060	High-Frequency Twin Triode
6X4	6063	Full Wave High Vac. Rect.
6AT6	6066	Duplex Diode High-Mu Tri.
12AU7	6067	Medium-Mu Twin Triode
12AY7	6072	Twin Triode
6AS7-G	6080	Low-Mu Twin Tri. Pwr. Amp.
5Y3-GT	6087	Full Wave High Vac. Rect.
6AQ5	6094	Beam Power Amplifier
6J6	6101	Medium-Mu Twin Triode
5Y3	6106	Full Wave Rectifier
	6111	Medium-Mu Twin Triode
	6112	High-Mu Twin Triode
6SL7-GT	6113	High-Mu Twin Triode
6AC7	6134	R.F. Pentode
6C4	6135	Medium-Mu Triode
6AU6	6136	Sharp Cut-Off R.F. Pentode
6SK7	6137	Remote Cut-Off R.F. Pent.
12AT7	6201	High Frequency Twin Triode
6X4	6202	Full Wave High Vac. Rect.
6BH6	6265	Sharp Cut-Off R.F. Pentode
2C51	6385	High Frequency Twin Triode
2C51	6386	High Frequency Twin Triode

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